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Expendable Hydrophone for Sonobuoy Application

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Standards Branch
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17 September 1973

NAVAL RESEARCH LABORATORY
Underwater Sound Reference Division
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13. ABSTRACT

A low-cost, low-noise, high-sensitivity hydrophone has been developed for possible application in an expendable, air-deployable, passive sonar array system. An acoustic element consisting of two Type III ceramic radially poled cylinders was combined with a low-noise, high-gain preamplifier to produce a hydrophone with a sensitivity of -149 dB re 1 V/μPa, operating frequency range of 10 Hz to 3 kHz, and depth capability of 4550 m. In addition to a description of the hydrophone and its operating specifications, a discussion of design criteria and prototype selection is included.

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Abstract

A low-cost, low-noise, high-sensitivity hydrophone has been developed for possible application in an expendable, air-deployable, passive sonar array system. An acoustic element consisting of two Type III ceramic radially poled cylinders was combined with a low-noise, high-gain preamplifier to produce a hydrophone with a sensitivity of -149 dB re 1 V/μPa, operating frequency range of 10 Hz to 3 kHz, and depth capability of 4550 m. In addition to a description of the hydrophone and its operating specifications, a discussion of design criteria and prototype selection is included.

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EXPENDABLE HYDROPHONE FOR SONOBUOY APPLICATION

Introduction

The objective of the work reported here has been to develop a hydrophone to satisfy guide specifications provided by the Naval Ordnance Laboratory (NOL) for a hydrophone that can be used in an expendable, air-droppable, passive sonar array system. The result is a hydrophone that has the advantages of low cost, low self noise, and high sensitivity.

The guide specifications provided by NOL are:

Sensitivity:	-149 dB re 1 V/μPa
Bandwidth:	10 Hz to 3 kHz
Directionality:	Omnidirectional to within 1 dB over a bandwidth of 10 Hz to 2 kHz
Operating depth:	Maximum of 4550 m, which is equivalent to 46 MPa (6670 psi)
Vibration sensitivity:	Less than 10 dB re 1 V/g
Reproducibility:	Unit-to-unit variation shall be less than that required to pass a -40 dB null balance test over the reduced bandwidth of 10 Hz to 1 kHz and a -30 dB null balance test over the remaining band of 1 kHz to 3 kHz
Phase matching:	Units shall track within ±3° of each other over the full bandwidth 10 Hz to 3 kHz
Self noise:	Noise power spectral density referred to input acoustic power shall be 10 dB below sea state zero noise at all frequencies
Output d-c offset:	Less than 5 V to ground
Output impedance:	Typically 50 Ω
Size:	Maximum 2.54 cm diameter by 7.6 cm long
Mass:	250 g or less
Operating temperature:	0 to 30°C
Cost:	Minimal

The order in which the items appear in this specification should not be construed as an indication of relative importance. There are, in addition, other requirements that are not explicitly stated, but, nevertheless

are important. These requirements include such characteristics as long shelf life, operational lifetime of at least 72 hours, and sufficient ruggedness to withstand field use and air deployment.

Succeeding sections of the report will discuss how the guide specifications can be met, discuss which guide specifications cannot be met simultaneously because of inherent incompatibilities and describe several hydrophone models, describe the construction of the model that most nearly satisfies all the guide specifications, and, finally, describe an area for possible further development.

Design Considerations

The hydrophone actually consists of two well-defined components--the acoustic element and the preamplifier. Among the decisions to be made for the acoustic element are choices of material, configuration, dimensions, and polarization. For the preamplifier, selections include electrical components, layout, gain, and self noise. The choices can be made only after a thorough analysis of the guide specifications that have been listed. This analysis is presented in the following paragraphs where the various items are considered in the order in which a logical design concept proceeded by process of elimination rather than by relative importance of the various aspects. Cost was considered a prime factor throughout because this hydrophone derives its usefulness by being inexpensive and expendable.

Size

Size is considered first because it determines the configuration and dimensions and, to a large extent, the sensitivity of the acoustic element. The diameter dimension is considered critical and must not exceed 2.54 cm. The maximum length called for is 7.6 cm; however, this requirement can be relaxed by as much as a factor of two, if necessary.

Sensitivity

The required over-all sensitivity, -149 dB re 1 V/μPa, can be achieved by a combination of preamplifier gain and piezoelectric ceramic sensitivity. The design philosophy in this case is that given a preamplifier, the gain should be maximized with respect to the output self noise, thereby reducing the sensitivity required of the ceramic element. Typically, a gain of about 40 dB can be obtained from a low-cost preamplifier while still maintaining a relatively low output noise. Thus, a ceramic element sensitivity of about -189 dB re 1 V/μPa would be required.

A choice exists as to the size, shape, and material of the acoustic element. Table I summarizes the sensitivity and capacitance for various feasible acoustic element configurations. The designations of Type I, II, and III refer to ceramic materials as described in MIL-STD-1376(SHIPS) [1]. The dimensions used in Table I were derived by choosing the maximum element dimension so that when the element was covered by a protective barrier, the 2.54-cm size limitation would not be exceeded. The

Table I. Sensitivity and capacitance for various acoustic element configurations.

	Disks, axially poled, 22.2 mm in diameter			Capped cylinders, radially poled, 22.2 mm O.D. and 6.35 mm long			Striped capped cylinders (6 stripes), circumferentially poled, 22.2 mm O.D. and 63.5 mm long			Spheres, radially poled, 22.2 mm O.D.		
Ceramic	Thickness (mm)	Sens. (dB re 1 V/μPa)	Cap. (pF)	I.D. (mm)	Sens. (dB re 1 V/μPa)	Cap. (pF)	I.D. (mm)	Sens. (dB re 1 V/μPa)	Cap. (pF)	I.D. (mm)	Sens. (dB re 1 V/μPa)	Cap. (pF)
Type I	10.0	-208	430	15.9	-197	1300	15.9	-184	220	15.9	-201	3900
	12.7	-206	340	19.1	-196	2900	12.7	-190	370	19.1	-199	9400
Type II	10.0	-214	580	15.9	-196	1800	15.9	-185	300	15.9	-200	5300
	12.7	-212	460	19.1	-195	4000	12.7	-190	510	19.1	-199	13000
Type III	10.0	-208	350	15.9	-199	1100	15.9	-185	180	15.9	-202	3200
	12.7	-206	300	19.1	-197	2400	12.7	-191	300	19.1	-201	7700
Lead meta-	10.0	-191	90	15.9	-218	240	15.9	-179	40	15.9	-220	700
niobate	12.7	-189	70	19.1	-207	530	12.7	-184	70	19.1	-213	1700

other dimensions such as length, inside diameter, and thickness then were chosen for optimum sensitivity and capacitance while reasonable pressure-resistant qualities were maintained. The calculations for sensitivity and capacitance are shown in Appendix A.

Capped striped cylinders and lead metaniobate disks would appear to be the only single elements with sufficient sensitivity; however, single elements of lower sensitivity can be wired electrically in series for greater sensitivity but with a decrease in capacitance. For example, two elements in series result in a sensitivity gain of 6 dB and 50% lower capacitance; three in series give a gain of 9.5 dB and a 67% lower capacitance. Therefore, a stack of radially polarized capped cylinders of Type I, II, or III ceramic wired in series could be used with a resulting sensitivity of about -189 dB re 1 V/μPa. The same is true for ceramic spheres, except that three or four in series conflict with the size limitation and are not as economical as capped cylinders.

It appears, then, that lead metaniobate disks and Types I, II, and III ferroelectric ceramic capped cylinders, either radially or circumferentially polarized, would satisfy size and sensitivity requirements for the acoustic element.

Operating Depth

The maximum expected operating depth of 4550 m (15,000 ft) in sea water is equivalent to 46 MPa (6670 psi). It would be preferred that the hydrophone be insensitive to changes in hydrostatic pressure; however, the large hydrostatic pressure at depth can cause the sensitivity of the acoustic element to change and it literally will crush an unprotected preamplifier. For this reason, the preamplifier must be protected by a rigid pressure vessel or encapsulated in a rigid epoxy. Cost considerations suggest the epoxy encapsulation.

The acoustic element configurations listed in Table I have sufficient physical strength to resist crushing. The effect of excessively high hydrostatic pressure is to depolarize the element, thereby producing a loss of its piezoelectric characteristics and its sensitivity.

The calculations for the stresses generated within the acoustic element by the hydrostatic pressure are presented in Appendix B. The calculations indicated have been performed for the acoustic elements that have been considered to be possibilities for hydrophone development. The values of the three components of compressive stress encountered by capped cylinders under a hydrostatic pressure of 46 MPa are given in Table II. These values were compared with the maximum allowable stresses in Table B-1, and thus the range of acoustic element possibilities was further reduced as shown in Table III.

Bandwidth

The free-field voltage sensitivity of a piezoelectric element is independent of frequency at frequencies far below the primary resonance

Table II. Maximum compressive stresses (in megapascals) contributing to depolarization of a capped cylinder (b = 11.1 mm and P = 46 MPa).

Polarization	Stress	a = 6.35 mm	a = 7.9 mm	a = 9.5 mm
Radial	$T_{\parallel}$; T_r [a]		46	46
	$T_{\perp}$; T_θ [b]		190	360
	T_z [c]		95	180
Circumferential	$T_{\parallel}$; T_θ [b]	137	190	
	$T_{\perp}$; T_r [a]	46	46	
	T_z [c]	68	95	

[a] T_r = 0 at r = 1 and is a maximum at r = b.

[b] T_θ is maximum at r = a and minimum at r = b.

[c] T_z is constant, independent of r.

frequency. If the resonance is sufficiently high, the specified bandwidth, 10 Hz to 3 kHz, can be satisfied. The primary resonances are presented in Table IV for the configurations under consideration. Since all the resonances are well above the operating bandwidth (10 Hz to 3 kHz), no problem of limited operation should be encountered. The equations and appropriate ceramic characteristics are given for the calculation of the primary resonance frequencies in Appendix [illegible].

Directionality

A disk or capped cylinder of the dimensions previously discussed will operate in a volume expander mode and will appear omnidirectional if the maximum element dimension is much less than the wavelength of sound in the medium at the working frequency. At 3 kHz, the wavelength in water at 4°C is approximately 475 mm. The maximum dimension of the disk or capped cylinders under consideration is the circumference, which is about 70 mm. Thus, these element configurations are expected to be omnidirectional within the frequency range from 10 Hz to 3 kHz.

Table III. Decision on hydrophone application based on liklihood of depolarization of element under hydrostatic pressure of 46 MPa.

Ceramic	Disks, axially poled, 22.2 mm diam. — Thickness (mm)	Disks — Application?	Capped cylinders, radially poled, 22.2 mm O.D., 6.35 mm long — I.D. (mm)	Capped cylinders — Application?	Striped capped cylinders, circumferentially poled, 22.2 mm O.D., 63.5 mm long — I.D. (mm)	Striped capped cylinders — Application?	Spheres, radially poled
Type I	Insufficient sensitivity		15.9	No	15.9	No	Insufficient sensitivity
			19.1	No	12.7	No	
Type II			15.9	No	15.9	No	
			19.1	No	12.7	No	
Type III			15.9	Possibly	15.9	Probable	
			19.1	No	12.7	Probable	
Lead metaniobate	10.0	Yes	Insufficient sensitivity		15.9	Probable	
	12.7	Yes			12.7	Probable	

Table IV. Approximate primary longitudinal and radial resonances for selected acoustic elements, 22.2 mm O.D.

Ceramic	Configuration	I.D. (mm)	Length (mm)	Long. res. freq. (kHz)	Rad. res. freq. (kHz)
Type III	Cylinder, radially poled	15.9	6.35	273	58
	Cylinder,	15.9	63.5	27	71
	circumf. poled	12.7	63.5	27	78
Lead meta-	Disk, axially		10.0	154	79
niobate	poled		12.7	121	7[illegible]
	Cylinder, circumf. poled	15.9	63.5	21	51
		12.7	63.5	21	56

Cost

The total cost of the hydrophone comes primarily from the acoustic element, preamplifier, and labor, and secondarily from epoxy, cylinder end caps, cables, and other miscellanea. Most of these costs are essentially fixed for a given preamplifier and assembly procedure. The major decision lies in the choice of acoustic element. Table V is a cost comparison of appropriate ceramic elements. It is based on vendor quotations and prices of similar items recently purchased. The prices are also based on quantities of ten thousand.

It is immediately obvious that lead metaniobate circumferentially polarized cylinders are too expensive for this application. The Type III circumferentially polarized cylinders are much cheaper but are still more expensive than the disks. There would also be extra labor costs for the cylinders because of the necessity to wire the individual striped segments in proper sequence. Thus, they are eliminated because of high cost. Type III radially poled cylinders are individually the cheapest, but, because of their lower sensitivity, several must be used in series for each hydrophone. If three are wired in series, their total sensitivity would be about equal to that of the lead metaniobate disks. The material cost would be a little more than one half that of the lead metaniobate disks; however, there would be extra labor costs from bonding and wiring the elements together, which could make the radially poled cylinders and the lead metaniobate disks comparable in cost.

Self Noise

Self noise is a product of the preamplifier only. Most of the self noise originates at the input stage. The acoustic element does not actively contribute to the self noise but does affect it by the amount of

Table V. Comparison of unit cost of selected ceramic elements purchased in lots of 10,000.

Ceramic	Disks, axially poled, 22.2 mm diameter		Capped cylinders, radially poled, 22.2 mm O.D., 15.9 mm I.D., 6.35 mm long	Striped capped cylinders, circumf. poled, 22.2 mm O.D., 63.5 mm long	
	Thickness (mm)	Unit cost	Unit cost	I.D. (mm)	Unit cost
Type III			$1.75	15.9	$11.25
				12.7	13.50
Lead metaniobate	10.0	$8.00		15.9	75.00
	12.7	$10.00		12.7	90.00

impedance loading on the input. In general, the higher the input load capacitance, the quieter the preamplifier. This implies that the radially polarized cylinder with its higher capacitance (see Table I) would result in quieter operation than would the disk.

Although the actual self noise is of electronic origin, it often is related to an equivalent acoustic noise pressure level. It is assumed for the purpose of definition of this relation that the preamplifier is noise free and the hydrophone detects a certain specified level of acoustic pressure. In this way, a more realistic lower limit on sensitivity to true signal can be established.

The conversion between sea state noise and preamplifier noise is discussed in more detail in Appendix D. When converted, the noise specification calls for an output noise voltage of less than -69 dB re 1 V. If the preamplifier gain is about 40 dB, then the critical input stage must have components with a combined noise level below -109 dB re 1 V.

Reproducibility

A 40-dB null balance is equivalent to a 2% variation between hydrophones and a 30-dB null balance is equivalent to a 6% variation. Appendix E gives the proof of equivalence. Such variation can arise in the ceramic element or in the preamplifier. Careful design and construction of the preamplifier can make the ceramic element the dominant factor. The sensitivity of a ceramic element is due largely to the piezoelectric constants g_{31} and g_{33} and, to a lesser extent, to the dielectric constant ε_{33}, as seen in Appendix A. Hence, any variability in the sensitivity can be traced to those constants. Unfortunately, the manufacture of ceramics entails slightly different compositions and production

techniques such that the characteristics of ceramics differ not only from one manufacturer to another but also from one batch to another by the same manufacturer [2]. Ceramic characteristics change with age as well and at different rates for different manufacturers.

It is not unrealistic to expect the sensitivity of ceramic elements to vary by 15% over a long period of production by several manufacturers [2].

The reproducibility specification can be met in several ways. One is to obtain all elements from one manufacturer's single batch. Of course, this may not be possible for very large quantities, but fewer individual batches should result in a smaller variation. Individual variabilities could be compensated by preamplifier gain adjustment or capacitor "shading" of the element. Aged ceramic elements also could be used to alleviate the problem.

Phase Matching

In the frequency range from 10 Hz to 3 kHz, the sound wavelength is much larger than the element; therefore, a disk or capped cylinder should respond to a sound wave of this length with no phase shift. Some phase difference may exist among preamplifiers, but, with proper design and component tolerance, the difference should be less than the $\pm 3^\circ$ required in this frequency range.

Vibration Sensitivity

Vibration of the hydrophone while deployed in the ocean would come from wave motion, suspension cable strumming by currents, antenna strumming by wind, and other unknown factors. A hydrophone can be made less sensitive to vibration by making it more massive (by Newton's second law, a given force will produce less acceleration). Mass and size limitations, however, eliminate this solution. Hydrophones can be made insensitive to vibration also by arranging an even number of acoustic elements symmetrically about the center of gravity. In this way, the effects of acceleration upon elements on one side of the center of gravity will be canceled by opposite effects of acceleration upon elements on the other side. The disadvantage of this approach is greater cost and size.

The most satisfactory solution, in view of the other specifications, is to decouple the hydrophone array from the cable suspension system, thereby decreasing the amount of vibration to which the hydrophone would be subjected.

Output Impedance and d-c Offset

A low output impedance is typical of preamplifiers and should present no problem. The output d-c offset voltage can be held to practically zero by a blocking capacitor on the preamplifier output.

Mass

A small mass is compatible with the small size and cost and should be no problem.

Operating Temperature

The hydrophone will experience temperatures from 0 to 30°C near the ocean surface, depending upon the location of operation. At any appreciable depth, the operating temperature will be near 4°C. These temperatures will produce no appreciable effect on the ceramic element or the preamplifier.

Summary of Design Criteria

The design considerations discussed above have been directed mostly toward the ceramic sensor element because this is where the alternatives exist. Once an element configuration is found feasible, a suitable preamplifier can be obtained by modifying a basic design to suit the requirements. The many possible acoustic element configurations have been limited by the various guide specifications. Table VI summarizes the elimination process. Lead metaniobate disks and the Type III radially poled capped cylinders appear to be worthy of application in this hydrophone development.

Hydrophone Prototypes

Several hydrophone models were designed, constructed, and tested. The characteristics of the most promising ones will be discussed here. The preamplifier was designed for compatibility with all of the acoustic element configurations and will be described separately, because the one basic design was used with all acoustic elements.

Table VI. Summary of design criteria applied to ceramic elements.

	Disks, axially poled	Capped cylinders		Spheres, radially poled
Ceramic	diam.×thick. (mm)	radially poled OD×ID×length (mm)	circumf. poled	
Type I		Pressure sensitive		
Type II	Insufficient sensitivity			Insufficient sensitivity
Type III		22.2×15.9×6.35	High cost	
Lead metaniobate	22.2×10.0 22.2×12.7	Insufficient sensitivity		

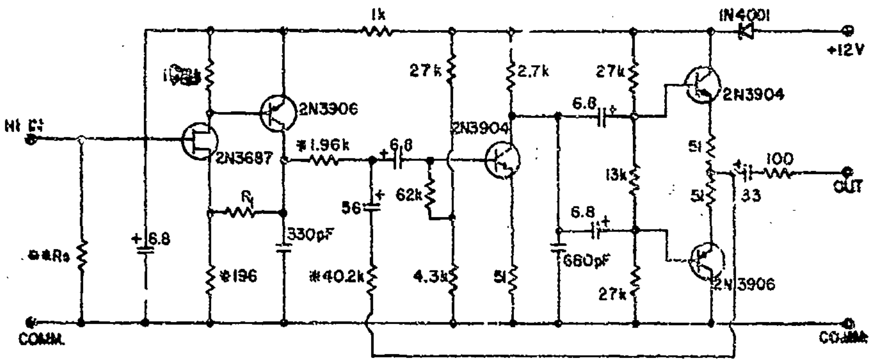


Fig. 1. Schematic of hydrophone preamplifier.

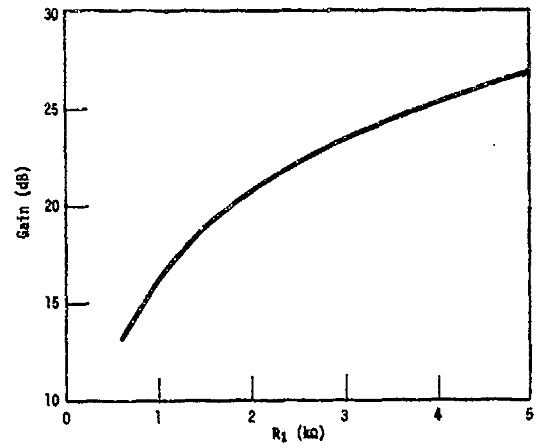
Preamplifier

A line schematic of the preamplifier is shown in Fig. 1. It is basically a straightforward design incoporating a low-noise field effect transistor (FET) input, two stages of amplification, and a balanced low-impedance output. The preamplifier is approximately 57 mm long by 16 mm wide by 12 mm thick with components mounted on both sides of the circuit board to conserve space. The circuit is potted in Eccobond 51 epoxy for protection from hydrostatic pressure.

Two factors related to hydrophone application that affect the choice of input impedance are charge dissipation and low-frequency roll-off of sensitivity. Charge is generated by the piezoelectric effect in the acoustic element when the pressure increases as the hydrophone sinks to operating depth, and also by the pyroelectric effect as the temperature of the hydrophone changes to that of the surrounding water. The resulting voltage can rise to very appreciable levels and saturate the FET, thereby preventing it from functioning and can, in fact, permanently damage it. There are several ways to dissipate the charge as it is generated. The resistive path to ground is used here. From the standpoint of charge dissipation alone, it would be desirable that the resistive shunt be of low value; however, the sensitivity of the acoustic element to underwater sound is adversely affected by a low-resistance shunt because the signal also is shunted. The input impedance of the preamplifier must be much larger than the low-frequency impedance of the acoustic element to avoid a low-frequency sensitivity roll-off. Calculations of the charge build-up are given in the first part of Appendix F. The effect of the impedance on the sensitivity is shown in the second part of Appendix F.

The shunt resistor satisfies both the above considerations if a value of 5000 MΩ is used with the lead metaniobate acoustic element and 900 MΩ with the Type III cylinder series element.

Fig. 2. First-stage preamplifier gain as a function of feedback resistor R_1 value.



The FET and a 2N3906 transistor provide the first stage of amplification with a gain of approximately 20 to 25 dB. The value of the precision resistor R_1 is set to give the proper over-all gain as required by the acoustic element. A graph of the gain of the first stage as a function of the resistance is given in Fig. 2. The second stage of amplification is derived from a 2N3904 transistor and a bootstrap between the output and second stage input. A precision resistor of 40.2 kΩ in the bootstrap produces a second stage gain of 20 dB.

The output is balanced and provided with a d-c blocking capacitor and 100-Ω line resistor. The blocking capacitor satisfies the specification of less than 5 V output d-c offset. The output impedance of 100 Ω is necessary to prevent self oscillation.

A three-conductor cable serves for preamplifier power, common ground, and signal. It is not considered good practice in low-noise hydrophones to use a coaxial cable where both B+ voltage and a-c signal are on a common conductor.

The noise appearing at the output terminals of the preamplifier is primarily the sum of the shunt resistor thermal noise and the FET self noise multiplied by the preamplifier gain. The FET chosen is a Siliconex 2N3687, which has a satisfactory self noise and cost figure. The calculations involved in selecting a FET with sufficiently low self noise are presented in the third part of Appendix F.

The total rms noise voltage spectral density for the preamplifier is shown in Fig. 3. The data are based on noise measurements made on three individual preamplifiers with the appropriate capacitive and resistive loads and gains to simulate the desired acoustic elements. Internal variances of the different preamplifiers produced somewhat different curves under identical conditions; therefore, the noise voltage spectral density is represented by bands rather than by lines in Fig. 3. A comparison is made also to the maximum noise permitted by the guide specification. The specification is exceeded by the preamplifier for the lead metaniobate acoustic element at frequencies below 40 Hz.

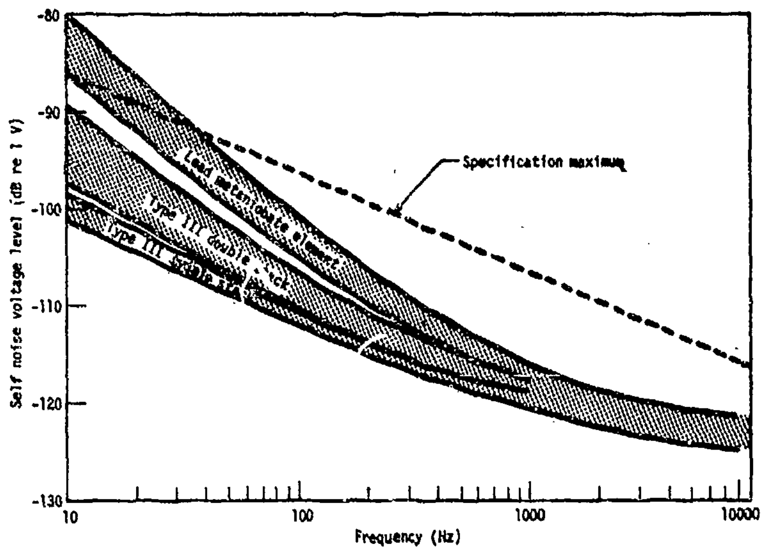


Fig. 3. Hydrophone rms noise voltage spectral density.

The dynamic range of the preamplifier is limited at the lower level by the sum of the self noise and the sea state acoustic noise. The upper level is limited by the inability of the preamplifier to pass a sufficiently undistorted signal. This upper limit has been determined by measuring the amplitude of the input sine wave that causes a 1% distortion in the output wave form. The rms value of the input signal was -35±1 dB re 1 V at all frequencies from 10 Hz to 3 kHz for the three preamplifiers. For an acoustic element sensitivity of -191 dB re 1 V/μPa, this value would correspond to a sound-pressure level of approximately 156 dB re 1 μPa. The preamplifier will continue to operate at input levels as high as -20 dB re 1 V, but with considerable distortion and deviations in gain and phase caused by saturation. Within the dynamic range of the preamplifier, the gain is constant to within ±0.1 dB.

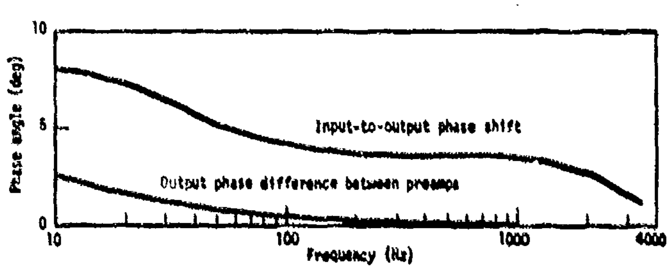


Fig. 4. Average phase shift of preamplifier.

A phase shift does occur between the input signal and preamplifier output, but the shift appears to be a design constant. The average input-output phase shift of any individual preamplifier and the average phase difference between the outputs of any two preamplifiers are given in Fig. 4. The specifications of gain and phase matching are met.

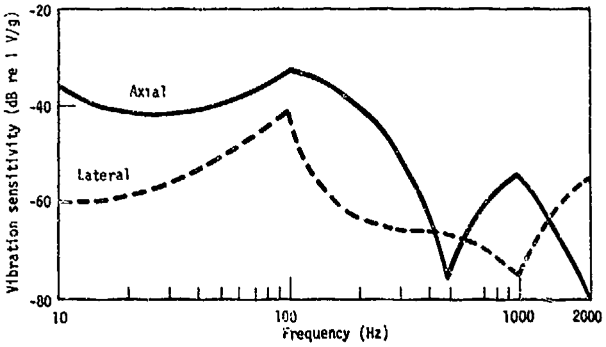


Fig. 5. Preamplifier sensitivity to vibration in lateral and axial directions.

The sensitivity of the preamplifier to vibration was measured in the axial and lateral directions. As expected, the vibration sensitivity is quite low in comparison with that of the acoustic elements. The results are shown in Fig. 5.

A list of preamplifier components and costs is given in Table VII. The estimated costs are based on quantities of ten thousand. Labor costs for constructing the preamplifiers can be reduced considerably by production line techniques to about equal that of the components.

Ceramic Acoustic Element Type III

The Type III ceramic, radially poled, capped cylinder, discussed previously, is useful in this application only if several are wired in series for greater sensitivity. A twin stack (two cylinders in series) and a triple stack (three cylinders in series) are illustrated in Fig. 6. The dimensions of the cylinders are 22.2 mm O.D. by 15.9 mm I.D. by 6.35 mm long. The end caps of alumina (AlSiMag 771 by American Lava Corp.) are 22.2 mm in diameter by 4 mm thick.

The calculated sensitivity of one cylinder has been given in Table I as -199 dB re 1 V/μPa. Two cylinders in series should produce a sensitivity of -193 dB re 1 V/μPa and three in series, a sensitivity of -189.5 dB re 1 V/μPa. Actual measurements indicate sensitivities of -193.1 dB re 1 V/μPa for the twin stack and -189.8 dB re 1 V/μPa for the triple stack. The sensitivity is independent of frequency between 10 Hz and 3 kHz except for the expected low-frequency roll-off caused by the RC combination of the preamplifier shunt resistor and the ceramic cylinder capacitance. The extent of this roll-off at 10 Hz is 0.3 dB for the twin

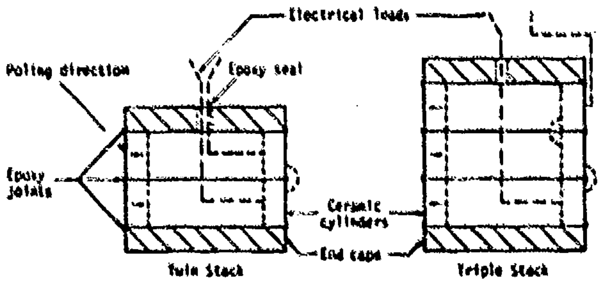


Fig. 6. Twin and triple stacks of Type III ceramic, radially poled, capped cylinders.

Table VII. Preamplifier parts and cost list.

Component	Number	Unit cost	Total cost
Resistors, precision:			
R_S (900 MΩ or 5000 MΩ, depending on acoustic element)	1	$1.75	$1.75
R_1 (exact value depends on gain)	1	.15	.15
196 Ω	1	.15	.15
1960 Ω	1	.15	.15
40.2 kΩ	1	.15	.15
Resistors, nonprecision:			
50 Ω	3	.03	.09
100 Ω	1	.03	.03
1 kΩ	1	.03	.03
2.7 kΩ	1	.03	.03
4.3 kΩ	1	.03	.03
13 kΩ	1	.03	.03
17.8 kΩ	1	.03	.03
27 kΩ	3	.03	.09
62 kΩ	1	.03	.03
Capacitors:			
6.8 μF	4	.22	.88
30 μF	1	.24	.24
56 μF	1	.24	.24
330 pF	1	.09	.09
680 pF	1	.09	.09
Transistors:			
2N3687	1	1.00	1.00
2N3904	2	.28	.56
2N3906	2	.29	.58
Diodes:			
1N4001	1	.15	.15
Sensitized P.C. board	1	.40	.40
Total estimated cost			$6.97

stack, which has a measured capacitance of 560 pF, and 0.4 dB for the triple stack with 400 pF, when the shunt resistor is 900 MΩ.

The sensitivity decreases approximately linearly with increasing hydrostatic pressure by 1 dB between atmospheric pressure and 46 MPa. The cylinder sensitivity is omnidirectional within 0.5 dB at all pressures throughout the frequency range from 10 Hz to 3 kHz.

The measured sensitivities of supposedly identical cylinder stacks were all within 0.2 dB of each other at atmospheric pressure when made from ceramic elements of the same batch. As shown in Appendix E, this reproducibility is equivalent to a -40 dB null balance. At a hydrostatic pressure of 46 MPa, the variation between stacks increased to 0.4 dB, which is equivalent to a -33 dB null balance. This change with pressure probably is due to differences in epoxy bonds between cylinders and end caps and is largely unavoidable. Greater differences in sensitivities existed when stacks were made of cylinders from different manufacturers. Differences of 1 dB in sensitivity between stacks were not uncommon. This difference corresponds to a -25 dB null balance.

When the stacks were subjected to an acoustic signal between 10 Hz and 3 kHz, the electrical output tracked within 1° of each other.

The vibration sensitivities of the twin stack and triple stack are shown in Figs. 7 and 8, respectively. For the complete hydrophone to meet the specification of less than +10 dB re 1 V/g, the vibration sensitivity of the acoustic element must be less than the specification by at least the preamplifier gain. Thus, vibration sensitivity levels of about -34 dB re 1 V/g for the twin stack and about -31 dB re 1 V/g for the triple stack are critical. Both stacks exceed these levels at about 100 to 200 Hz.

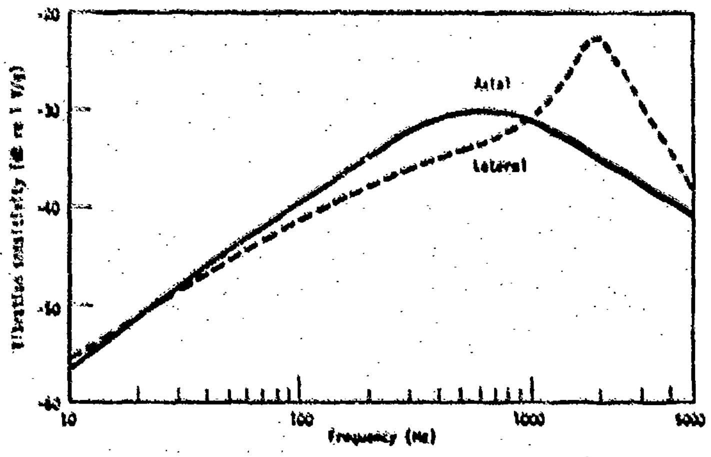


Fig. 7. Vibration sensitivity of a twin stack of Type III ceramic cylinders.

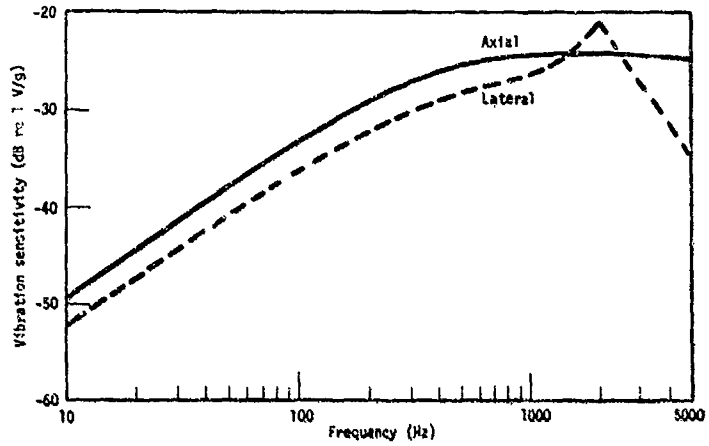


Fig. 8. Vibration sensitivity of a triple stack of Type III ceramic cylinders.

In quantities of ten thousand, a cylinder costs $1.75 and an alumina end cap costs $0.045. Therefore, the material cost of a twin stack should be about $3.60 and a triple stack about $5.35. These material costs are based on manufacturer's quotations [3,4]. The extent of the labor involved is to solder leads to the proper electrodes and to cement the cylinders and end caps together. An estimate of a reasonable production line labor charge is $0.75 for the twin stack and $1.00 for the triple stack. This brings the total cost of a twin stack to approximately $4.35 and a triple stack to approximately $6.35.

Lead Metaniobate Acoustic Element

The axially polarized lead metaniobate disk is a simpler sensor element than the capped cylinder in that connections need be made only to the electrodes to have a working sound detector. The theoretical sensitivity of a 12.7-mm thick disk is equal to that of a triple-cylinder stack. The primary disadvantage of lead metaniobate is its low dielectric constant. The disk capacitance is so low that quite often leakage capacitance is large enough to cause an appreciable loss in sensitivity. The calculated sensitivities and capacitances of a 12.7-mm and a 10-mm-thick disk are given in Table I. The measured values are -193 dB re 1 V/μPa and 100 pF for the 12.7-mm-thick disk and -193.5 dB re 1 V/μPa and 120 pF for the 10-mm-thick disk. The discrepancy between calculated and measured sensitivities is in good correlation with the differences in calculated and measured capacitances.

The sensitivity is omnidirectional. There was a gradual increase in sensitivity to the extent of 0.3 dB per decade of frequency between 10 Hz and 3 kHz in addition to the expected low-frequency roll-off. A 5000-MΩ bleed resistor was used in the preamplifier input for the reasons discussed in Appendix F. The RC low-frequency roll-off at 10 Hz was 0.3 dB

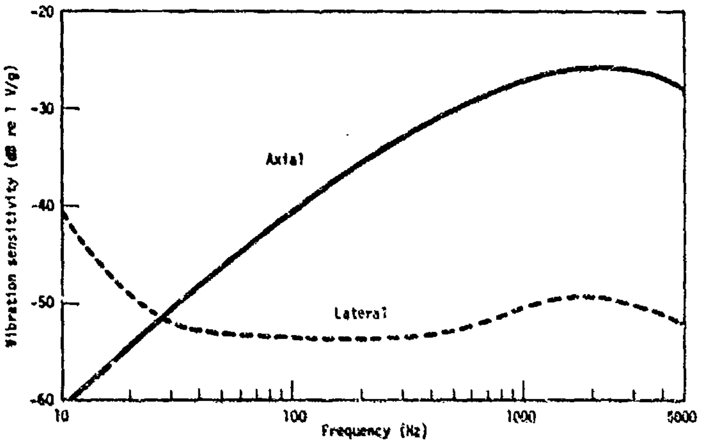


Fig. 9. Vibration sensitivity of a lead metaniobate disk.

for the 12.7-mm-thick disk and 0.2 dB for the 10-mm-thick disk. The sensitivity decreases approximately linearly with increasing hydrostatic pressure by 0.7 dB between atmospheric and 46 MPa.

The reproducibility of sensitivity for lead metaniobate disks is adversely affected by the inability to maintain stray capacitance within acceptable limits. As little as 10 pF stray capacitance is typical and amounts to 10% of the disk capacitance, which changes the measured sensitivity by about 1 dB. Thus the unit-to-unit variation could pass only a -25 dB null balance test.

The vibration sensitivity of a 12.7-mm-thick lead metaniobate disk is shown in Fig. 9. A vibration sensitivity level of -34 dB re 1 V/g is critical for the disk, if the complete hydrophone is to meet the guide specification. The disk exceeds this level between 200 and 300 Hz for vibration in the axial direction. Sensitivity to vibration in the lateral direction is quite low at all frequencies. The size of the disk is such that the disk could be oriented without violation of the over-all size limitation so that the dominant vibration present would be in the lateral direction.

Lead metaniobate disks, 10 mm and 12.7 mm in thickness, cost $8.00 and $10.00, respectively, in quantities of ten thousand [5]. Labor is not a factor because the preamplifier input leads need only be soldered to the disk electrodes.

Summary

Characteristics of the three hydrophone models are compared in Table VIII. None of the three meet all of the specifications, although the model containing the Type III twin stack acoustic element most nearly does so. The primary shortcoming is in the sensitivity to vibration. A hydrophone could be built to meet the vibration specification, but the resulting size and cost would be much greater. The total hydrophone cost given in Table VIII is somewhat relative because of the estimate of labor costs that are associated primarily with the preamplifier. The broad-band self noise of the hydrophone between 10 Hz and 3 kHz is less

Table VIII. Comparison of hydrophone models.

Characteristic	Type III ceramic: Twin stack	Type III ceramic: Triple stack	Lead metaniobate disk (12.7 mm)	Specification
Element sens. (re 1 V/μPa)	-193.1 dB	-189.8 dB	-193 dB	
Reproducibility, null-balance test:				
at atmospheric pressure	-40.0 dB	-40.0 dB	-25 dB	-40 dB
at 46 MPa	-33.0 dB	-33.0 dB	-25 dB	-40 dB
Change in sens. with pressure, 0-46 MPa	1.0 dB	1.0 dB	0.7 dB	
Preamplifier gain required to meet specification	+44.1 dB	+40.8 dB	+44 dB	
Hydrophone meets bandwidth requirement?	yes	yes	yes	10-3000 Hz
Omnidirection to within	0.5 dB	0.5 dB	0.5 dB	1 dB
Vibration sens. maximum (re 1 V/g):				
axial mode	+14.0 dB	+17.0 dB	+18 dB	+10 dB
lateral mode	+22.0 dB	+20.0 dB	+4 dB	+10 dB
Phase matched to	±2½°	±2½°	-	±3°
Broadband self noise (re 1 V) between 10 Hz and 3 kHz	-77.0 dB	-81.0 dB	-70 dB	-69 dB
Output d-c offset	0.225 V	0.225 V	0.225 V	<5 V
Output impedance	150 Ω	150 Ω	150 Ω	*50 Ω
Size:				
diameter	2.54 cm	2.54 cm	2.54 cm	2.54 cm
length	8.40 cm	9.00 cm	7.60 cm	7.60 cm
mass	100 g	110 g	90 g	<250 g
Hydrophone cost:				
acoustic element	$4.35	$6.35	$10.00	
preamplifier	6.97	6.97	6.97	
miscellaneous materials	.28	.28	.23	
labor (estimated)	7.00	7.00	7.00	
total	$18.60	$20.60	$24.20	minimal

*Typical.

for all three models than the specification; however, this is because the narrow-band noise is considerably below specification above 100 Hz. Actually, the narrow-band noise for the lead-metaniobate hydrophone is well above specification at frequencies below 50 Hz.

Hydrophone Construction

Mass production practices probably will differ considerably from the laboratory techniques on which the following discussion is based, but at least a basis that has produced working hydrophones is provided.

The hydrophone with the twin-cylinder stack acoustic element has been shown to satisfy most nearly the guide specifications. A first step in assembling the acoustic element is to bond the two cylinders together endwise. Epon VI (Hysol Epoxy Products) is a suitable bonding agent and is applied according to manufacturer's instructions. A small compressive force is applied during the cure to maintain alignment and to insure a uniform bond. The two cylinders should have opposite polarity to facilitate hook-up; that is, one cylinder should be polarized with the positive electrode on the inner diameter and the other with positive on the outer diameter.

Two possibilities exist for wiring the two cylinders together in series. In either case the stack should be oriented with respect to the preamplifier so that the positive electrode of the cylinder nearest the preamplifier is connected to the preamplifier input. This insures the outputs from all hydrophones are in phase.

a. The two cylinders can be wired as illustrated in Fig. 6. The outer-diameter electrodes are either soldered together by a jump lead or joined by a coat of conductive paint or epoxy which has a bulk resistivity equal to or less than 0.001 Ω-cm. The positive inner electrode is connected to the preamplifier signal input and the inner negative electrode to the preamplifier ground. The two leads pass through a hole in the end cap that must be hermetically sealed with Epon VI. The advantage of this arrangement is that the cylinder outer dimension defines the hydrophone outer diameter except for the protective over-all potting compound. The disadvantage of this approach is the extra labor involved with the end-cap electrical feedthrough.

b. The inner-diameter electrodes can be joined by soldering a lead between them or by painting a conducting path over the bond joint. A lead then is connected between the preamplifier signal input and the positive outer-diameter electrode of the cylinder nearest the preamplifier and a second lead between the preamplifier ground and the negative outer-diameter electrode of the other cylinder. The advantages of this method are that no feedthroughs are required in the end cap and the element is easier to assemble. The disadvantage is that the leads must pass between the cylinder and the maximum 2.54-cm dimension. Care must be taken that the leads are not exposed through the potting compound to the hydrostatic pressure and that they do not short circuit the outer electrodes of the cylinders.

After the stack is wired, the end caps are bonded to the cylinders with Epon VI. The connections between the twin stack and the preamplifier then can be completed. Next, the assembly is positioned in a mold that describes the finished dimensions of the hydrophone and is encapsulated in a suitable compound like Eccobond 51 (Emerson & Cuming). The potting forms the finished dimension of the hydrophone, seals the cable, forms a waterproof barrier, and protects the preamplifier from the hydrostatic pressure.

Before the assembly is encapsulated, all surfaces of the cable, preamplifier, and sensor element are cleaned of all flux and other contaminants.

The Eccobond 51 is mixed according to the manufacturer's recommendations. The container used for mixing is free of any coatings or other contaminants and is of sufficient size for degassing the mix. After the compound is thoroughly mixed with a glass or metal rod, it is degassed. The initial evacuation stage must be gradual to prevent the froth from overflowing the container. Evacuation should continue until all major bubbles stop forming and vacuum of about 0.3 Torr pressure is maintained for approximately 5 minutes.

After initial evacuation of the mix, it is poured into the mold with care taken to entrap as little air as possible. The potted assembly then is evacuated for 5 to 10 minutes until the major bubbles have been removed.

The vacuum system used to degas the encapsulant should have sufficient capacity to pump down to 1 Torr within 3 minutes. Such a system is necessary to insure that the finished assembly be free of any entrapped gases or voids that could produce unwanted low-frequency resonances.

The preamplifier circuit board and location of components are shown in Fig. 10. Again, it should be commented that the preamplifier layout is adequate but not necessarily optimum. Figure 11 is an illustration of steps encountered in assembling the components into a working hydrophone.

Future Development

The part of the hydrophone that probably can undergo further development is the preamplifier. Integrated circuits may be more feasible for large quantities with the result of reductions in cost and size. This possibility should be investigated before any large procurement proceeds. It is conceivable that the preamplifier can be reduced to a size that can be mounted on an end cap inside the ceramic cylinder stack. The total hydrophone size then would be approximately 2.5 cm diameter by 2.5 cm long after potting.

References

[1] MIL-STD-1376(SHIPS), "Piezoelectric Ceramic for Sonar Transducers," 21 Dec 1970.

[2] R. W. Timme, "Low Electrical Field Characteristics of Piezoelectric Ceramic Rings," NRL Report 7528, 5 Jan 1973 (AD-907 068L).

[3] Type III cylinder quotation from Channel Industries, Santa Barbara, California.

[4] Alumina end cap quotation from American Lava Corp., Chattanooga, Tennessee.

[5] Lead metaniobate disk quotation from Gulton Industries, Metuchen, New Jersey.

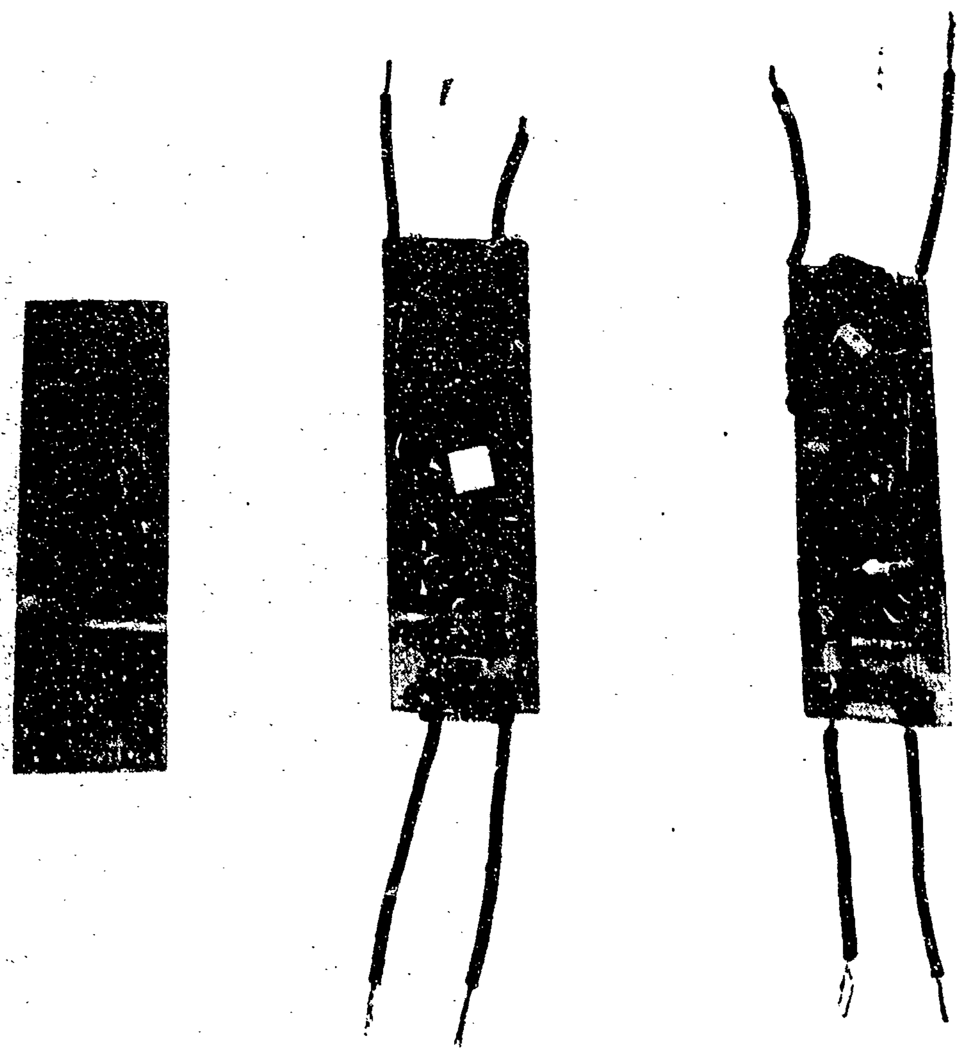


Fig. 10. Preamplifier circuit board.

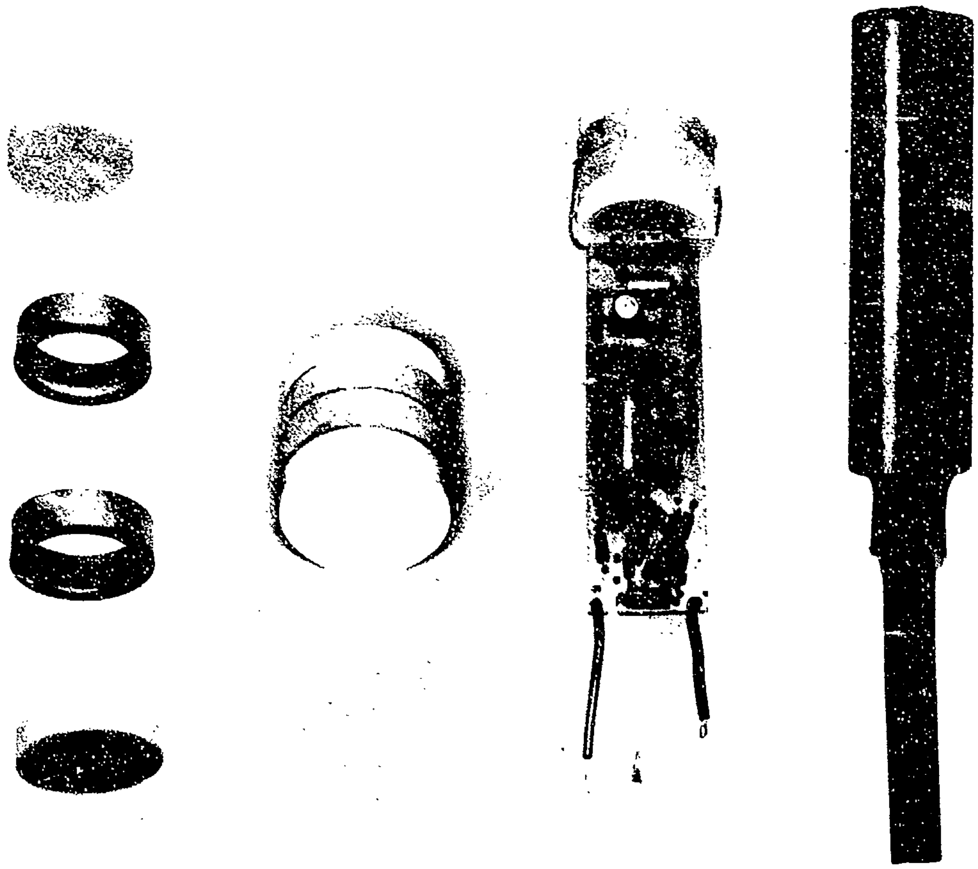


Fig. 11. Assembly of hydrophone.

Appendix A

Calculation of Sensitivity and Capacitance

Symbol	*Definition*
M	free-field voltage sensitivity
C	capacitance
e	open-circuit voltage
p	incident sound pressure
g_{33}, g_{31}	piezoelectric constants
ε_{33}	dielectric constant
t	thickness between electroded surfaces
a	inner radius
b	outer radius
A	cross-sectional area of electroded surface
ℓ	length of cylinder
N	number of stripes

The free-field voltage sensitivity for a piezoelectric ceramic disk or plate can be calculated from an expression that is derived from the equation of state relating the electric field generated across the ceramic element to the incident stress and strain:

$$M = e/p = (g_{33} + 2g_{31})t. \tag{A-1}$$

The capacitance can be obtained from the simple relation for the parallel plate capacitor:

$$C = \varepsilon_{33}A/t. \tag{A-2}$$

The expression for the free-field voltage sensitivity of a capped cylindrical ceramic tube has been derived by Langevin [A-1]:

$$M = b\left(g_{33}\frac{1 - a/b}{1 + a/b} + g_{31}\frac{2 + a/b}{1 + a/b}\right). \tag{A-3}$$

The capacitance is given by

$$C = \frac{2\pi\varepsilon_{33}\ell}{\ln(b/a)}. \tag{A-4}$$

Langevin's derivations were extended to striped tubes with circumferential polarization. The sensitivity and capacitance are given by

$$M = \frac{1}{N}\frac{2\pi b}{\ln(b/a)}\left\{g_{31}\frac{2 - a/b}{1 + a/b} + g_{33}\right\} \tag{A-5}$$

and

$$C = \frac{N\varepsilon_{33}\ell}{2\pi}\ln(b/a). \tag{A-6}$$

The free-field voltage sensitivity of a ceramic sphere has been derived by Anan'eva [A-2]:

$$M = \frac{b}{q^2+q+1}\left\{\frac{q^2+q-2}{2}g_{33} - \frac{q^2+q+4}{2}g_{31}\right\}, \text{ where } q = a/b. \tag{A-7}$$

The capacitance of a sphere is given by

$$C = \frac{4\pi\varepsilon_{33}ab}{b - a}. \tag{A-8}$$

The piezoelectric constants g_{33} and g_{31} and the dielectric constant ε_{33} for the ceramic Types I, II, III, and lead metaniobate have the nominal values given in Table A-I.

Table A-I. Piezoelectric constants and dielectric constant for several ceramic materials.

Material	g_{33} ($V \cdot m^{-1} Pa^{-1}$)	g_{31} ($V \cdot m^{-1} Pa^{-1}$)	ε_{33} ($F \cdot m^{-1} \times 10^{-8}$)
Type I	0.026	-0.0110	1.1
Type II	0.025	-0.0115	1.5
Type III	0.022	-0.0090	0.9
Lead metaniobate	0.036	-0.0045	0.2

References

[A-1] R. A. Langevin, "The Electro-Acoustic Sensitivity of Cylindrical Ceramic Tubes," J. Acoust. Soc. Amer. 26, 421-427 (1954).

[A-2] A. A. Anan'eva, *Ceramic Acoustic Detectors* (Consultants Bureau, New York, 1965), p. 46.

Appendix B

Calculation of Stresses due to Hydrostatic Pressure

Symbol	*Definition*
T_r	stress in radial direction of cylinder
T_θ	stress in circumferential direction of cylinder
T_Z	stress in axial direction of cylinder
$T_\parallel$	stress parallel to direction of polarization
$T_\perp$	stress perpendicular to direction of polarization
P	hydrostatic pressure
a	inner radius of cylinder
b	outer radius of cylinder
r	distance from center of cylinder along radius

The stresses in a capped cylinder as derived by Langevin [B-1] are:

$$T_r = -P\frac{b^2}{b^2 - a^2}(1 - a^2/r^2); \tag{B-1}$$

$$T_\theta = -P\frac{b^2}{b^2 - a^2}(1 + a^2/r^2); \tag{B-2}$$

$$T_Z = -P\frac{b^2}{b^2 - a^2}. \tag{B-3}$$

The maximum stress that a capped cylinder can experience without undergoing depolarization depends on the direction of poling. A radially polarized cylinder experiences a radia stress T_r parallel to the direction of poling and combined stresses of T_θ and T_Z perpendicular to the direction of poling. A striped cylinder is circumferentially polarized and experiences a stress T_θ parallel to the direction of poling and bombined stresses T_r and T_Z perpendicular to the direction of poling.

Unfortunately, little work has been done to determine the compressive stress limits for the different ceramic types and configurations. Clevite [B-2] has determined for ceramic Types I and II the compressive stress at which the dielectric and piezoelectric constants have changed several percent without recovery and this they have defined as the maximum allowable stress for Type III or lead metaniobate; however, one can

infer from the high electrical field characteristics that Type III and lead metaniobate are successively more resistant to depoling than Type I [B-3].

The values given in Table B-I are the result of one-dimensional stress measurements. Because the stresses encountered within the capped cylinders are two-dimensional, the stresses parallel and perpendicular to the poled direction should not be compared directly with those in Table B-I. It is not well understood how the individual components of stress calculated from Eqs. (B-1,2,3) should be combined to represent the resultant stress leading to depolarization. Empirical data strongly suggest that ceramics are more resistant to depolarization by a two-dimensional stress than by a one-dimensional one. Until more definitive work is done, the only recourse at this point is to obtain a relative, order-of-magnitude comparison of the Table B-I data with the calculated values of T_r, T_θ, and T_z, assuming (incorrectly) that the stresses are completely independent of each other. This is done in Table B-II.

The compressive stresses sustained by a solid disk can be obtained from Eqs. (B-1,2,3) in the limit a = 0 and are just equal to the hydrostatic pressure P. The maximum compressive stress in this mode given by Clevite [B-2] is 345 MPa (50,000 psi) for Type I and 138 MPa (20,000 psi) for Type II ceramic. Again, data are not available for Type III and lead metaniobate, but again it is expected that Type III is better than Type I and lead metaniobate is better than Type III.

Table B-I. Maximum allowable stress for poled ceramics.

Stress	Type I	Type II	Type III	Lead metaniobate
$T_\parallel$ (max)	83 MPa (12,000 psi)	35 MPa (5,000 psi)	>Type I	>Type III
$T_\perp$ (max)	55 MPa (8,000 psi)	14 MPa (2,000 psi)	>Type I	>Type III

References

[B-1] R. A. Langevin, "The Electro-Acoustic Sensitivity of Cylindrical Ceramic Tubes," J. Acoust. Soc. Amer. 26, 421-427 (1954)

[B-2] Clevite Corp., Piezoelectric Div., "Piezoelectric Technology Data for Designers" (Bedford, Ohio, 1965).

[B-3] Gulton Industries, Inc., "Glennite Piezoceramics--Catalog H-700," p. 16.

Table B-II. Compressive stresses contributing to depolarization.

Polarization	Stress	r = a	r = b	Common multiplicative factor
Radial	$T_{\parallel}$; T_r	0	$1 - a^2/b^2$	$P \dfrac{1}{1 - a^2/b^2}$
	$T_{\perp}$; T_θ	2	$1 + a^2/b^2$	
	T_Z	1	1	
Circumferential	$T_{\parallel}$; T_θ	2	$1 + a^2/b^2$	
	$T_{\perp}$; T_r	0	$1 - a^2/b^2$	
	T_Z	1	1	

Appendix C

Resonance Frequencies

Symbol	*Definition*
f_r	resonance frequency
ρ	density
s_{11}^E s_{33}^E	elastic moduli at constant electric field
k_{33}	electromechanical coupling factor
σ^E	Poisson's ratio at constant electric field
η	disk radial mode Bessel function
t, ℓ, D	thickness, length, and mean diameter, respectively, of element

The resonance frequencies are determined by the size and configuration of the acoustic element. There are many possible modes of vibration, but the ones of real concern here are the thickness mode of a disk, the radial mode of a disk, the longitudinal mode of a cylinder, and the radial mode of a cylinder. In the simplest case, only one mode of vibration will be excited at a time. This occurs when the dimension determining the resonance is much different from other dimensions. Whenever the simple expressions indicate that resonance frequencies in different modes are similar or identical, there will be coupling of energy between modes and the simple expressions will not give correct results. However, the simplified equations will provide information as to whether resonance is far above the intended range of operation.

Equations for the resonance frequency have been derived by Berlincourt *et al.* [C-1] for the following cases of interest. The values obtained will be for the fundamental, or primary, resonance.

Axial (thickness) mode

$$f_r = (1/2t)[\rho s_{33}^E(1 - k_{33}^2)]^{-\frac{1}{2}} \tag{C-1}$$

Radial mode

$$f_r = (\eta/\pi D)(\rho s_{11}^E[1 - (\sigma^E)^2])^{-\frac{1}{2}} \; ; \; \eta = (1 - \sigma^E) \frac{J_1(\omega a/c)}{J_0(\omega a/c)} \tag{C-2}$$

Cylinder (radially polarized), radial mode

$$f_r = (1/\pi D)(\rho s_{11}^E)^{-\frac{1}{2}} \tag{C-3}$$

Cylinder (circumferentially polarized), radial mode

$$f_r = (1/\pi D)[\rho s_{33}^E(1 - k_{33}^2)]^{-\frac{1}{2}} \quad \text{(C-4)}$$

Cylinder (independent of polarization), length mode

$$f_r = (1/2\ell)(\rho s_{11}^E)^{-\frac{1}{2}} \quad \text{(C-5)}$$

The parameters for use in these equations are given in Table C-I. Only Type III and lead metaniobate are considered because the other types already have been shown to be inadequate for this application.

Table C-I. Selected parameters of Type III and lead metaniobate.

Parameter	Type III	Lead metaniobate
ρ (kg/m^3)	7500	5800
s_{11}^E (m^2/N)	11.1×10^{-12}	25.0×10^{-12}
s_{33}^E (m^2/N)	12.2×10^{-12}	21.3×10^{-12}
k_{33}	0.63	0.38
σ^E	0.37	0.27
η	2.08	2.03

Reference

[C-1] D. Berlincourt, D. Curran, and H. Jaffe, "Piezoelectric and Piezomagnetic Materials, in *Physical Acoustics*, Vol. I-A, W. P. Mason, ed. (Academic Press, New York, 1964), pp. 221-231.

Appendix D

Hydrophone Self Noise

The guide specifications require an acoustic noise at least 10 dB below the light shipping sea state zero composite curve of Urick [D-1]. The sea state zero curve is shown on Fig. D-1. According to the "pink noise tangent" principle [D-2], this composite curve can be represented by the pink noise slope (-10 dB per decade) indicated on Fig. D-1. The total noise pressure in the band between frequencies f_1 and f_1 is given by

$$p = p_0 \ln\sqrt{(f_2/f_1)}, \tag{D-1}$$

where p_0 is the noise pressure at 1 Hz. For the frequency range from 10 Hz to 3 kHz, the noise pressure is

$$p = +90 \text{ dB re } 1 \text{ V}/\mu\text{Pa}. \tag{D-2}$$

The specification calls for an equivalent input noise pressure of 10 dB below sea state zero; hence, the noise must be

$$p \leq +80 \text{ dB re } 1 \ \mu\text{Pa}. \tag{D-3}$$

If the hydrophone sensitivity is -149 dB re 1 V/μPa, then the rms output noise voltage must be

$$\begin{aligned} e_{rms} &\leq (-149 \text{ dB re } 1 \text{ V}/\mu\text{Pa} + 80 \text{ dB re } 1 \ \mu\text{Pa}) \\ &\leq -69 \text{ dB re } 1 \text{ V}. \end{aligned} \tag{D-4}$$

For purposes of preamplifier design and testing, it is convenient to plot the total rms output noise voltage as an output noise spectrum on a log voltage vs. log frequency curve. This is done in Fig. D-2.

References

[D-1] R. J. Urick, *Principles of Underwater Sound for Engineers* (McGraw-Hill, New York, 1967), p. 168.

[D-2] L. Smith and D. H. Sheingold, "Noise and Operational Amplifier Circuits," Analog Dialogue 3, 1-15 (1969).

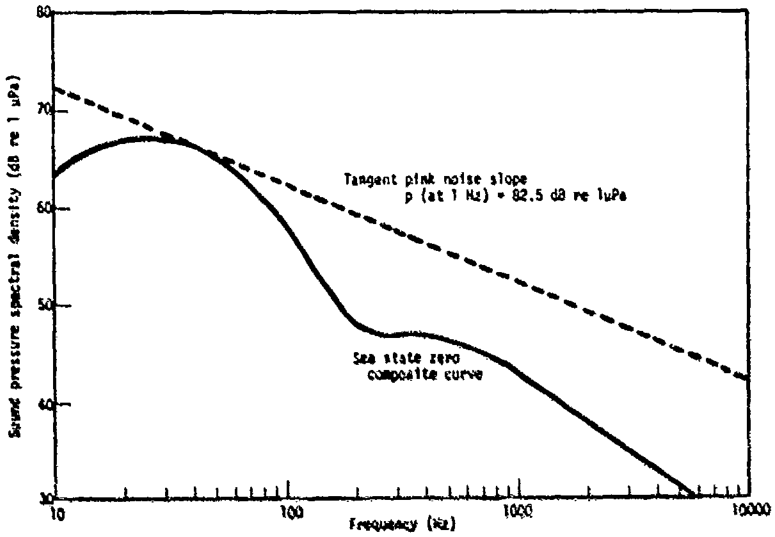


Fig. D-1. Ocean acoustic noise pressure.

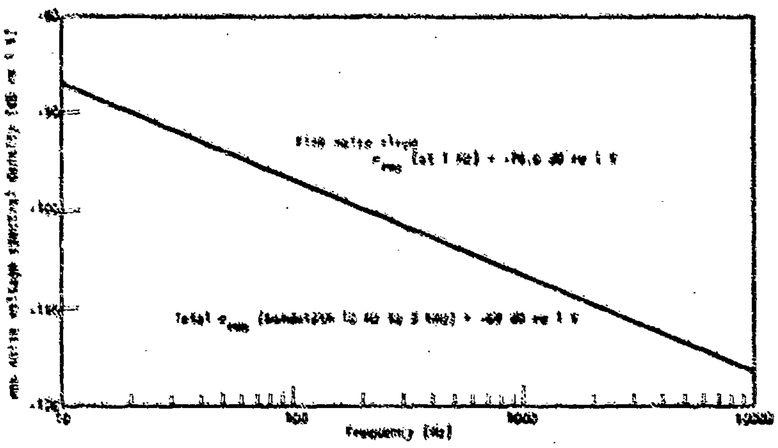


Fig. D-2. Maximum acceptable rms output noise voltage spectral density for hydrophone.

Appendix E

Null Balance Equivalent Calculations

Symbol	*Definition*
M_A	free-field voltage sensitivity of hydrophone A
M_B	free-field voltage sensitivity of hydrophone B

A null balance measurement (NBM) is made by determining the sum and difference sensitivities of two hydrophones:

$$\mathrm{NBM} = 20 \log \frac{M_A - M_B}{M_A + M_B} . \tag{E-1}$$

If the two hydrophones have exactly the same sensitivity, then there will be an infinite null, but this condition does not normally exist. The null balance requirement can be expressed also as a logarithmic variation (dB) or as a percentage variation. For example, let NBM $\leq$ 40 dB; then

$$20 \log \frac{M_A - M_B}{M_A + M_B} \leq -40 \text{ dB} \tag{E-2}$$

$$\log \frac{1 - M_B/M_A}{1 + M_B/M_A} \leq -2 \tag{E-3}$$

$$\frac{1 - M_B/M_A}{1 + M_B/M_A} \leq 0.01 \tag{E-4}$$

$$\frac{M_B}{M_A} \geq 0.98 = 2\% \text{ variation} \tag{E-5}$$

$$20 \log \frac{M_B}{M_A} \geq 20 \log 0.98 = 0.2\text{-db variation} \tag{E-6}$$

A second example can be solved in a similar manner:

NBM $\leq$ -30 dB

$$\frac{M_B}{M_A} \geq 0.94 = 6\% \text{ variation} \tag{E-7}$$

$$20 \log \frac{M_B}{M_A} \geq 20 \log 0.94 \approx 0.5\text{-dB variation.} \tag{E-8}$$

Appendix F

Preamplifier Design Calculations

1. Voltage generation and dissipation as a result of changes in hydrostatic pressure and temperature.

The hydrophone will be dropped into the water and deployed at some depth ℓ. The hydrostatic pressure and temperature change will generate a charge and voltage at the preamplifier input. The effect of the temperature change could add or subtract from the effect of the pressure change, depending upon whether the temperature increased or decreased and upon the element configuration. Either condition could be experienced, so the worst case should be expected; that is, that the effects add.

Let:

$D \equiv d\ell/dt$, time rate of descent

$B \equiv dP/d\ell$, rate of pressure change with depth

$M \equiv de/dP$, piezoelectric sensitivity of acoustic element (change in voltage with pressure)

$F \equiv dT/dt$, time rate of temperature change

$N \equiv de/dT$, pyroelectric sensitivity of acoustic element (change in voltage with temperature)

Then the rate of voltage increase due to charge generation by the piezoelectric and pyroelectric effects will be

$$A \equiv de/dt = MBD + NF. \tag{F-1}$$

The acoustic element and resistive shunt form a simple parallel RC circuit relative to the preamplifier FET. The voltage generated at the FET will decrease with time as the charge leaks through the resistance to ground.

$$de/dt = -e/RC. \tag{F-2}$$

The voltage at any time t is given by the differential equation formed by combining Eqs. (F-1) and (F-2):

$$de/dt = A - e/RC. \tag{F-3}$$

A solution for Eq. (F-3) for any time after the hydrophone touches water at $t = 0$ is

$$\begin{aligned} e = {} & ARC[1 - \exp(-t/RC)]\theta(t_0 - t) \\ & + ARC[1 - \exp(-t_0/RC)]\{\exp[-(t - t_0)/RC]\}\theta(t - t_0) \end{aligned} \tag{F-4}$$

where t_0 is the time when the hydrophone reaches operating depth and temperature and $\theta(t,t_0)$ is a function such that its value is unity when its argument is positive and zero when its argument is negative. It is imperative that the generated voltage e not exceed some critical value e' that would permanently damage the FET. Therefore, the first term of Eq. (F-4) must satisfy the relation

$$ARC[1 - \exp(-t/RC)] < e'. \tag{F-5}$$

The maximum value occurs when $t_0 >> RC$.

$$\lim_{t \to t_0 >> RC} ARC[1 - \exp(-t/RC)] \to ARC. \tag{F-6}$$

Thus,

$$ARC < e', \tag{F-7}$$

which places the restriction upon the shunt resistance that

$$R < e'/AC. \tag{F-8}$$

There exists a range of voltage between a saturation or blocking voltage e_b and the critical voltage e' such that the FET is "blocked," or inoperative, but not permanently damaged. If $ARC[1 - \exp(-t_0/RC)] > e_b$, then a period known as the "dead" time must pass before the hydrophone again is operational. The second term of Eq. (F-4) describes the decay of the voltage after generation has ceased. Generally, if the condition in Eq. (F-8) is satisfied, the dead time will be minimal. For this specific application, the following estimates have been made:

$D \approx 1$ m/sec

$B \approx 0.01$ MPa/m $= 10^4$ Pa/m

$M \approx -192$ dB re 1 V/μPa $= 2.5\times10^{-4}$ V/Pa

$F \approx 50°C/200$ sec $= 0.25°C$/sec

$N \approx 72$ V/°C for a 3.2-mm-thick-wall Type III cylinder.

From Eq. (F-1),

$$\begin{aligned} A &= MBD + NF \\ &= (2.5 + 18) \text{ V/sec} \\ &= 20.5 \text{ V/sec} \end{aligned}$$

$e' \approx 50$ V (for a Siliconex 2N3687).

Therefore, from Eq. (F-8),

$$RC < 2.44 \text{ sec.} \tag{F-9}$$

The values of B, D, N, and F are based on estimates of conditions possibly encountered, so it is appropriate that a safety factor be included to further limit the value of RC:

$$RC < 0.6 \text{ sec.} \tag{F-10}$$

Maximum values of the bleed resistor at the preamplifier input now can be calculated:

$$\begin{aligned} R &\leq 6.7\times10^9\ \Omega \text{ for a lead metaniobate disk;} \\ &\leq 1.6\times10^9\ \Omega \text{ for three Type III cylinders in series;} \\ &\leq 1.1\times10^9\ \Omega \text{ for two Type III cylinders in series.} \end{aligned} \tag{F-11}$$

2. *Sensitivity roll-off at low frequencies*

The impedance of the acoustic element is an inverse function of frequency and must be much less than the bleed resistor to avoid an unacceptable low-frequency roll-off (LFRO). The loss in sensitivity is given by

$$\text{LFRO} = -20 \log (1 + 1/\omega RC). \tag{F-12}$$

If an arbitrary limit of 0.5 dB at 10 Hz on sensitivity loss is chosen, then the minimum values of the shunt resistance are established:

$$\begin{aligned} R &\geq 3.0\times10^9\ \Omega \text{ for a lead netaniobate disk;} \\ R &\geq 0.73\times10^9\ \Omega \text{ for three Type III cylinders in series;} \\ R &\geq 0.49\times10^9\ \Omega \text{ for two Type III cylinders in series.} \end{aligned} \tag{F-13}$$

3. *Self noise at the input stage*

Thermal noise from the shunt resistor is a function of frequency as given by Eq. (F-14) because it is in parallel with the capacitive acoustic element:

$$e_{rms} = (2kT/\pi C)^{\frac{1}{2}} (\tan^{-1}\omega_2 RC - \tan^{-1}\omega_1 RC)^{\frac{1}{2}}, \tag{F-14}$$

where e_{rms} is the rms thermal noise voltage in a bandwidth defined by angular frequencies ω_1 and ω_2; C is the capacitance of the acoustic element, R is shunt resistance; $k = 1.37\times10^{-23}$J/K is Boltzmann's constant; and T is temperature in kelvin. The thermal noise is plotted as a function of frequency in Fig. F-1 for the values of R and C for the lead metaniobate and Type III ceramic elements:

Lead metaniobate: R = 5000 MΩ
C = 90 pF

Type III cylinders: R = 900 MΩ
C = 550 pF (two in series)
C = 367 pF (three in series)

To obtain a value for the acceptable FET self noise, the resistor thermal noise and preamplifier gain can be subtracted from the guide specification in Fig. D-2. The results are the three curves in Fig. F-2. There is a separate curve for each of the different acoustic elements because of the different capacitances, bleed resistors, and gains. The cross-hatched region in Fig. F-2 is a composite self noise curve representing actual measured values for five Siliconex 2N3687 FET's. Other FET's that have a self noise as good or better and a comparable cost include the Siliconex 2N3460 and 2N4338.

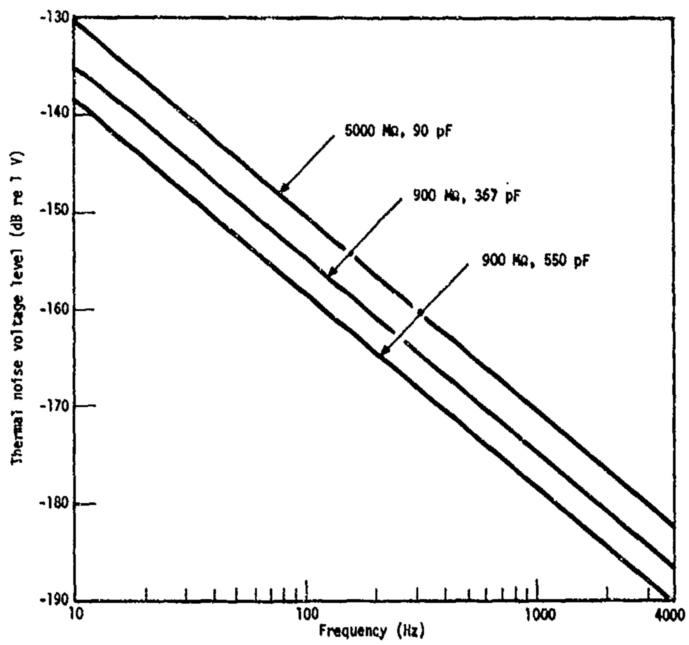


Fig. F-1. Thermal noise at preamplifier input from theoretical calculation.

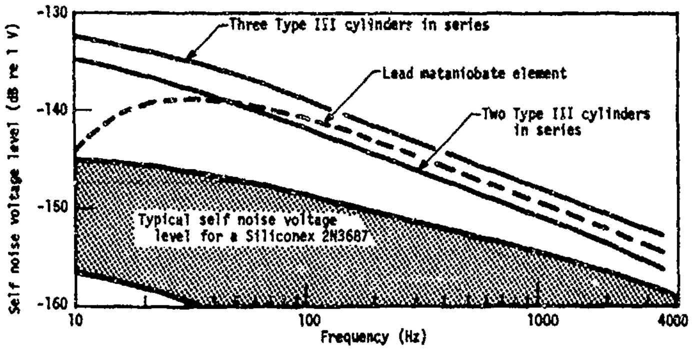


Fig. F-2. Maximum acceptable FET self noise for various acoustic elements.